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Efficient Linearization of Microwave Power Amplifiers

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Introduction: The growing use of multiple-carrier, complex (multi-level, multi-phase), spectrally efficient waveforms such as quadrature-amplitude-modulation (QAM) and code division multiple access (CDMA) in communication systems is placing a growing demand on the power efficiency and linearity of microwave power amplifiers. Continuing reliance on vacuum electronics amplifiers such as traveling-wave tube amplifiers (TWTA) in space-based transponders and ground terminals requires tube designers to constantly develop new techniques to improve the efficiency and linearity of devices. To satisfy performance requirements, there is an increasing trend of designers incorporating pre- or post-linearization modules with the power amplifiers to improve overall system efficiency and linearity.[1] Signal predistortion is a simple and effective linearization technique that has been used successfully for both solid-state power amplifiers (SSPA) and TWTAs.

The most commonly used predistortion linearization scheme is an analog predistortion linearizer utilizing a third-order nonlinearity. The nonlinearity is usually realized with either two anti-parallel diodes, an FET channel, or a low-power solid-state amplifier driven into compression. Third-order linearizers are reasonably effective at suppressing nonlinear distortion at low drive powers. Close to saturation, however, a higher-order nonlinearity is necessary for effective linearization. Predistortion linearizers with individually adjustable coefficients up to the fifth-order have been reported in the literature, but they are considerably more complex than third-order linearizers. Furthermore, it is prohibitively difficult to extend such a configuration much beyond a fifth-order implementation. We have developed a novel technique for realizing predistortion linearizers with orders greater than or equal to five using cascaded third-order linearizers.[2] The advantage of this approach is the relative simplicity of the third-order modules and the extensibility of the technique to cost-effective, arbitrarily higher-order nonlinearities.

Cascaded Third-Order Linearization: A baseband block model for a predistortion linearizer with both third- and fifth-order nonlinearities is shown in Fig. 6(a). A third-order linearizer has only the third-order term. A fifth-order linearizer has both the third- and fifth-order terms, which are independently adjustable. The challenge in construction of a fifth- or higher-order linearizer is to obtain the corresponding independently adjustable nonlinear components. The degree of difficulty increases exponentially with the degree of nonlinearity.

To simplify the realization of a fifth-order linearizer, two third-order linearizers can be placed in cascade to obtain both a third-order nonlinearity and a fifth-order nonlinearity (Fig. 6(b)). The appropriate amplitudes and phases of the third- and fifth-order components can be obtained by simultaneously adjusting the third-order coefficients of the two cascaded linearizers. To realize functions with nonlinearities higher than fifth-order, three or more third-order linearizers can be cascaded.

Experimental Verification: The effectiveness of cascaded third-order linearization was tested with five TWTs covering L-, C-, Ku- and Ka-band frequencies:

- L-band: Hughes 8537H helix TWT, 80 W CW, 1.53–1.65 GHz.
- C-band:
  - NRL/Northrop Grumman helix TWT, 140 W, 4–6 GHz.
  - Varian VZC6961K1 helix TWT, 40 W, 4–8 GHz.
- Ku-band: CPI VTU-6397 helix TWT, 13–14.75 GHz, 600 W.
- Ka-band: CPI VTA-6430 coupled-cavity TWT, 28–30 GHz, 500 W.

With the exception of the C-band Varian VZC6961K1, all of the TWTs were designed for communication applications (Fig. 7). The nonlinear code CHRISTINE was used to simulate the helix TWTs and CHRISTINE-CC was used to simulate the coupled-cavity TWT. The measured small- and large-signal performance of all the TWTs was in good agreement with the simulations.

Different types of waveforms relevant to communications applications were used for testing. They included single-tone, two-tone, and digitally modulated waveforms. The waveforms were generated in baseband with an Agilent E4438C vector signal generator. Predistortion was applied to the baseband waveforms before they were up-converted to the appropriate in-band microwave frequencies of the TWTs.

Depending on the test waveform, different metrics were used to evaluate the performance of the linearization schemes. These metrics include AM/AM conversion (characterizing the change in the amplitude of the output power as function of the amplitude of the input power) and AM/PM conversion (characterizing

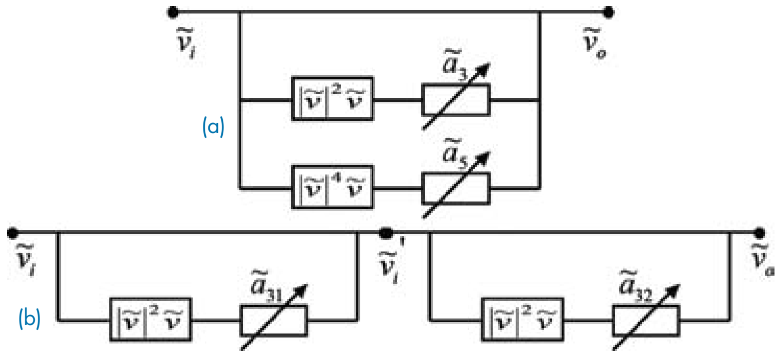

FIGURE 6
Baseband block model of predistortion linearizers. (a) A conventional parallel path linearizer with up to a fifth-order nonlinearity; (b) two cascaded third-order linearizers.

the change in the phase angle of the output waveform as a function of the amplitude of the input power) for single-tone waveforms; intermodulation distortion (generation of unwanted frequency components corresponding to the sum and difference of the driven frequencies) for two-tone waveforms; and adjacent-channel-power-ratio and error-vector-magnitude for digital waveforms. For all of the evaluation metrics, the improvement in gain compression through the use of linearization, in general, and the further improvement of fifth-order relative to third-order linearization are clearly demonstrated. Also note that there is almost no difference in performance between the fifth-order and cascaded third-order linearization functions, verifying that the cascaded third-order nonlinearity implementation functions as an efficient fifth-order nonlinearity generator.

Digital communication systems use advanced digital modulation techniques to increase spectral efficiency, to provide multiple access, and to improve reliability and anti-jamming capability. The presence of nonlinearities in the system not only degrades system performance but also generates spectral re-growth that can cause interference with neighboring systems. In Fig. 8, the spectra of 32-QAM waveforms measured at the output of the Varian C-band TWT are shown for the un-predistorted case and the third-order, fifth-order, and cascaded third-order predistorted cases. The presence of pedestals on the sides of the main lobe is an indication of spectral regrowth leading to potential interference with adjacent communications bands. In the figure, one can see the benefit of applying third-order predistortion, as it lowers the height of the pedestals by about a factor of ten. An additional factor of ten improvement can be observed for both the fifth-order and cascaded third-order linearization making a total of a hundred-fold improvement over the unpredistorted case.

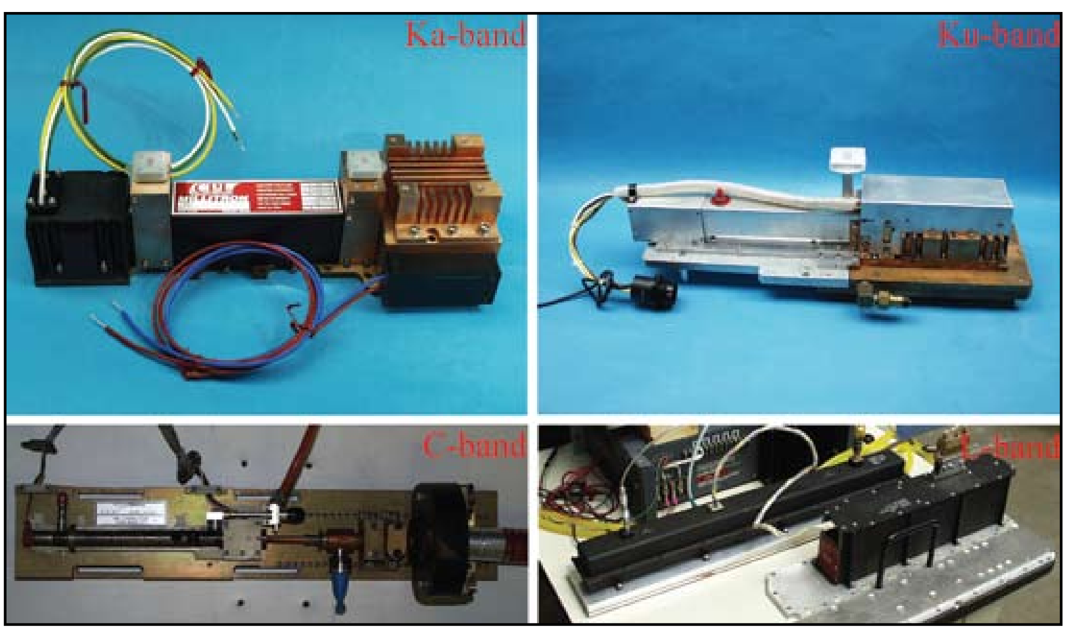

FIGURE 7
The four communication TWTs used in the evaluation of different predistortion schemes.

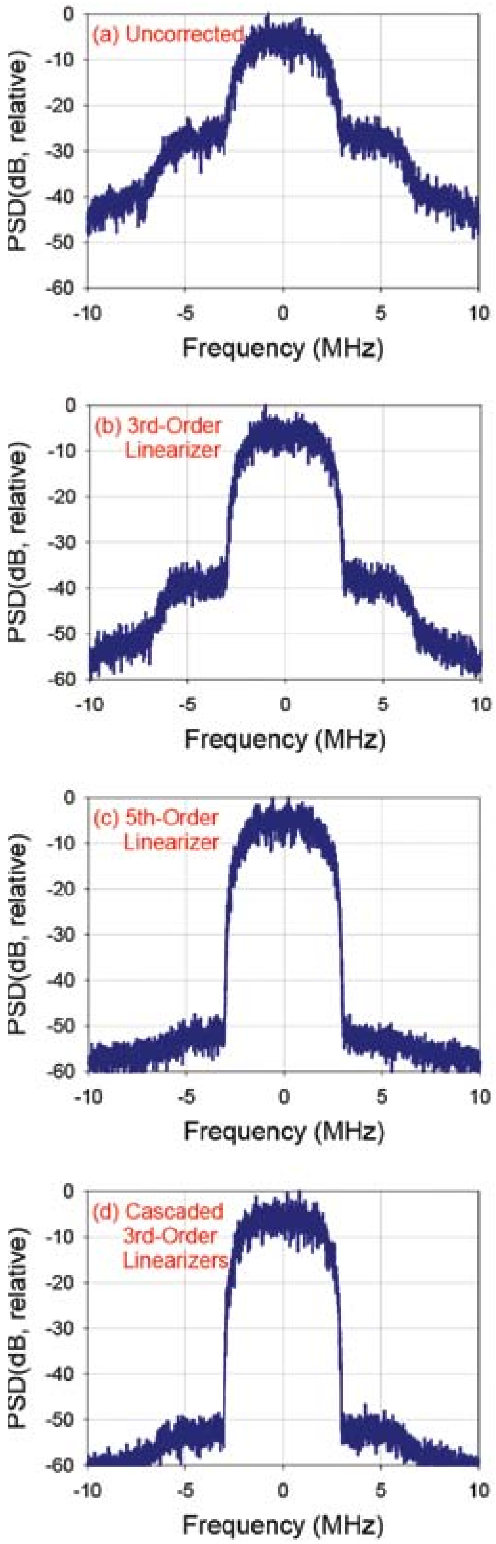

FIGURE 8
32-QAM spectra for the Varian C-band TWT at saturation. (a) No linearization; (b) third-order linearization; (c) fifth-order linearization; (d) cascaded third-order linearization. Note that while the fifth-order and cascaded third-order schemes have similar performance, the cascaded linearizer is simpler to implement.

Conclusion: We have developed a simple and efficient technique for realizing fifth- or higher-order predistortion linearization functions using cascaded third-order nonlinearities. The performance of two cascaded linearizers was experimentally demonstrated to be similar to that of a pure fifth-order implementation. The use of third-order modules has the potential advantage of being simpler to implement in hardware, and the cascading technique is, in principle, readily extensible to the implementation of cost-effective, arbitrarily higher-order linearizers.

[Sponsored by ONR]

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